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Title: Respiratory function in World-class powerlifters

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ABSTRACT

Resistance training activates the respiratory muscles providing a strength training stimulus similar to respiratory muscle strength training. We examined the effects of whole body resistance training upon respiratory muscle strength, pulmonary function and diaphragm thickness in World Class Powerlifters (POWER) and a control group (CON) matched for age, height and body mass with no history of strength or endurance training. Body composition was assessed using single frequency bioelectrical impedance. Maximal static volitional inspiratory ($P_{I,max}$) and expiratory ($P_{E,max}$) mouth pressures, diaphragm thickness (T_{di}) derived from ultrasound measurements and pulmonary function from maximal flow volume loops were measured. There were no differences in physical characteristics or pulmonary function between groups. $P_{I,max}$ (22%, $P<0.05$, effect size $d=1.13$), $P_{E,max}$ (16%, $P=0.07$, effect size $d=0.86$) and T_{di} (27%, $P<0.01$, effect size $d=1.59$) were greater in POWER than CON. Positive correlations were observed between T_{di} and body mass ($r=0.502$, $P<0.05$), $P_{I,max}$ ($r=0.518$, $P<0.05$) and $P_{E,max}$ ($r=0.671$, $P<0.01$). These data are the first to quantify the function of the respiratory system in elite resistance trained performers. We conclude for the first time that regular non-respiratory manoeuvres performed by World Class Powerlifters (i.e., squat, deadlift and bench press) improves respiratory muscle strength and diaphragm thickness but not pulmonary function. These data have significant health implications as Whole body-resistance training may be an appropriate training mode to attenuate the effects of respiratory muscle weakness experienced with ageing and some disease states and thus an effective adjunct to other training methods in clinical, healthy and elite athletes.

INTRODUCTION

Powerlifting comprises three closed kinetic chain exercises including the squat, bench press and deadlift (Harman et al 1989; Escamilla et al 2000; Garcia-Manso *et al*, 2008; Garhammer, 1993). The squat and deadlift primarily strengthen the lower extremities and posterior trunk whereas the bench press develops the upper extremities and anterior trunk (Escamilla *et al*, 2000, Hales et al 2009). When performing each of these techniques, the build-up of pressure within the abdominal cavity (intra-abdominal pressure; IAP) is considerable and occurs through contraction of the respiratory muscles, in particular the transverse abdominus and the diaphragm (DePalo *et al*, 2004; Al-Bilbeisi and McCool, 2000). The IAP establishes a rigid cylinder-like compartment within the abdomen where the transverse abdominals, diaphragm, rectus abdominals and vertebral column are considered the base, lid, anterior and posterior boundaries, respectively. It has been demonstrated that the IAP generated during these lifting manoeuvres significantly increases diaphragm activation which is unrelated to pulmonary ventilation (Hodges 1999) as measured by an increase in the transdiaphragmatic pressure (P_{di}) (Strongoli). The increased P_{di} plays two important roles. Firstly, as the diaphragm inserts directly on to the lumbar vertebrae P_{di} stiffens the vertebral column and resists spinal torsion and spinal disc injuries (Harman *et al*, 1989). Secondly, the P_{di} prevents the transmission of the IAP from the abdominal cavity to the thorax thus preventing lung collapse. Accordingly, repeated generation of pressures across the diaphragm in excess of 65% $P_{di,max}$ provides a strength training stimulus. This was demonstrated by a greater diaphragm thickness and inspiratory and expiratory muscle strength following 16 wk abdominal and upper arm resistance training in four previously un-trained individuals (DePalo *et al* 2004). Studies have also observed greater diaphragm thickness and respiratory muscle strength in adult recreational weight lifters (McCool x2) and cadavers of physical labourers (Arora). In addition, there is little research which has investigated the effects of resistance training upon pulmonary function. Functional residual capacity (FRC) remains unchanged following whole-body resistance training (DePalo) although specific respiratory muscle strength training has been shown to increase vital capacity (VC) and

total lung capacity (TLC) (Enright). This latter finding was likely due to an improved ability to inflate the lungs resulting from an increased respiratory muscle strength. Previous studies have focused on healthy untrained individuals, recreationally trained weight lifters or autopsy analyses. The effects of resistance training upon respiratory muscle and pulmonary function in World Class resistance trained individuals (Powerlifters) are however yet to be determined. Therefore, the aim of this study was to quantify for the first time the functional changes in the respiratory system of elite powerlifters. We hypothesised that chronic resistance training in World Class Powerlifters would increase respiratory muscle strength, diaphragm thickness and as a consequence pulmonary function compared to a matched untrained control group.

METHODS

Participants and experimental design

Following ethics approval and written informed consent, 10 male World Class Powerlifters (POWER) and 10 untrained individuals (control; CON) volunteered for the study (Table 1). Groups were matched for age, stature and body mass since these variables account for the most variance in pulmonary and respiratory muscle function according to the scaling principle of elastic similarity (McCool et al 1997; WILSON, QUANJER). Within POWER, seven had world titles and three had world records with no history of endurance or resistance training in CON. All subjects abstained from alcohol, caffeine and exercise in the 24 h prior to testing and arrived for testing 2 h post-prandial. During the testing battery, subjects completed in random order a body composition assessment using bioelectrical impedance, maximal flow-volume loops, maximal static inspiratory and expiratory muscle strength tests and ultrasound imaging of the diaphragm to determine diaphragm thickness.

Single frequency bioelectrical impedance

Single frequency bioelectrical impedance (BIA) was performed with the individual resting supine and in the neutral anatomical position. After the skin was shaved and cleaned whole-body resistance was measured using four surface electrodes placed on the right wrist and ankle according to the manufacturers guidelines (Bodystat 1500, Bodystat Ltd, British Isles). The two current application electrodes were placed just below the phalangeal-metacarpal joint of the third finger on the dorsal side of the hand and dorsal surface of the right foot proximal to the 2nd metatarsal-phalangeal joint. The two voltage-sensing detector electrodes were placed on the dorsal surface of the right wrist adjacent to the head of the ulna and on the anterior surface of the right ankle between the medial and lateral malleoli. Measurements of impedance were used to estimate total body water following the application of an electrical current of 50 kHz (400 μ A). Fat free mass was then calculated using an assumed hydration fraction for lean tissue (Bodystat 1500, Bodystat Ltd, British Isles).

Pulmonary and maximal inspiratory and expiratory muscle function

Pulmonary function was assessed by performing maximal flow volume loops in accordance with published guidelines (ATS/ERS 2005) using a digital volume transducer (Microlab, Micro Medical, Kent, UK) calibrated prior to all trials according to the manufacture's guidelines. Maximal static inspiratory ($P_{I,max}$) and expiratory ($P_{E,max}$) pressure was measured as an index of global inspiratory and expiratory muscle strength, respectively, using a hand-held mouth pressure meter fitted with a flanged mouthpiece (MicroRPM, Micro Medical, Kent, UK) calibrated over the physiological range using a digital pressure meter (Pirani strain gauge, MKS Barathon, MKS Instruments, MA, USA). The mouthpiece assembly incorporated a 1 mm orifice to prevent glottic closure and minimise the contribution of the buccal muscles during inspiratory efforts. Inspiratory and expiratory manoeuvres were performed standing, initiated from residual volume (RV) and TLC, respectively, and sustained for at least 1 s. A minimum of 3 and maximum of 8 manoeuvres were performed every 30 s, and the maximum value of 3 measures that varied by <5% was used for subsequent analysis (ATS/ERS 2002).

Diaphragm Imaging

In addition to measures of global respiratory muscle output (i.e., maximal volitional mouth pressures) diaphragm thickness (T_{di}) was assessed to provide information about the contractile properties of the muscle. Ultrasound measurement of T_{di} in the zone of apposition was assessed using a GE Logic Book XP portable ultrasound machine and 8 MHz linear array transducer (General Electric Company Healthcare, USA) in accordance with methods reported previously (Wait et al 1989). A small parts, musculo-skeletal manufacturer pre-set was selected with a single focal zone set to mid-screen and adjusted accordingly to the depth of the diaphragm. The subject was positioned upright with their right arm raised. Transducer position was then adjusted between the 7th to 10th intercostal space in the mid-axillary line where a coronal view of the right hemi-diaphragm was identified. Fine adjustment of the transducer position was used to place the

diaphragm in a horizontal plane across the field of view and to ensure a 90° angle of insonation. All measurements were recorded from FRC following a passive expiration from TLC. T_{di} was defined by on-screen callipers positioned at 90° to the diaphragm from the leading edge of the pleural membrane to the leading edge of the peritoneum membrane (see Figure 1). Measurements were repeated in triplicate and images saved to the system hard drive with the average of the three images used for subsequent analyses. Measurements were performed by an experienced clinical sonographer to minimise inter-tester and between subject random variation. The within-trial coefficient of variation for T_{di} was 2.6% with an intra-class correlation coefficient of 0.99.

Statistical analyses

Differences between groups (POWER vs. CON) were assessed using an independent samples *t*-test. Pearson's product moment correlation assessed the relationships between selected variables. Effect size was calculated post-hoc for selected variables using Cohen's *d* statistic. Statistical significance was set a-priori at $P \leq 0.05$ and data are presented as mean \pm SD unless stated otherwise.

RESULTS

Physical characteristics

Physical characteristics of both groups and the personal best scores for each of the powerlifting disciplines (squat, bench press, deadlift) including the total score (sum of all disciplines) is shown in Table 1. There were no differences in the physical characteristics between groups.

Respiratory Muscle Strength and Pulmonary Function

Maximal static inspiratory and expiratory mouth pressures and pulmonary function are shown in Table 2. Respiratory muscle strength values were within normal limits for CON, however, note that in POWER $P_{I,max}$ and $P_{E,max}$ were significantly greater than their predicted values. $P_{I,max}$ was 22% greater in POWER relative to CON ($P<0.05$) (effect size: $d=1.13$) and $P_{E,max}$ was 16% greater in POWER which approached significance ($P=0.07$) (effect size: $d=0.86$). Pulmonary function was within normal limits for both groups (Table 2) and there were no significant differences between the two groups for any variable.

Diaphragm Thickness

An example ultrasound image of diaphragm thickness (T_{di}) for a heavy (120 kg) and light (74 kg) powerlifter and matched control is shown in Figure 1. T_{di} was 3.10 ± 0.99 mm in POWER and 2.06 ± 0.33 mm in CON (27% difference; $P<0.01$).

Correlations

There was no relationship between T_{di} and stature ($r=-0.166$, $P=0.483$; Figure 2A) however, a significant positive correlation was observed between T_{di} and body mass ($r=0.502$, $P=0.024$; Figure 2B). There was a significant correlation between $P_{I,max}$ and T_{di} when data from both groups were pooled ($r=0.518$, $P=0.019$; Figure 2C) and there was a significant correlation between $P_{E,max}$ and T_{di} when data from both groups were pooled ($r=0.671$, $P=0.001$; Figure 2D). In POWER, there was a

significant positive correlation between the total weight lifted in competition (sum of deadlift, squat and bench press) and T_{di} ($r=0.825$, $P=0.003$) (Figure 3).

DISCUSSION

The aim of this study was to characterise pulmonary and respiratory muscle function of World Class Powerlifters relative to a matched untrained control group. The novel findings of this study were twofold. First, Powerlifters demonstrated superior respiratory muscle strength and diaphragm thickness than a matched untrained control group. Second, in disagreement to our hypothesis, there were no differences in pulmonary function between the Powerlifters and the untrained matched controls.

Respiratory muscle function

Our findings have demonstrated for the first time that World Class Powerlifters have greater global inspiratory (22%) and expiratory (16%) muscle strength as well as a greater diaphragm thickness (27%) than matched untrained controls. Although $P_{E,max}$ was not significantly greater in POWER, post-hoc calculation of effect size clearly demonstrates a very large effect (Cohen's $d=0.86$). We observed a relationship between inspiratory and expiratory muscle strength and diaphragm thickness (Figure 2C and D). We also present a relationship between diaphragm thickness and body mass (Figure 2B). These findings are in agreement with previous studies which have characterised respiratory muscle structure and dimensions in healthy and weight trained individuals (McCool et al. 1997). The notion that the respiratory muscles receive a training stimulus from whole-body resistance training has been demonstrated previously. In four healthy untrained individuals, 16 wk bicep curl exercise and abdominal crunches increased inspiratory (12%) and expiratory (13%) muscle strength and diaphragm thickness (11%) (De Palo et al). Similarly greater structural dimensions of the diaphragm (thickness, internal diameter and cross-sectional area) was shown in resistance trained individuals relative to controls (McCool et al 1997) and greater diaphragm muscle mass in cadavers of physical labourers and muscular individuals (Arora and Rochester 1982). Furthermore exercises which engage the trunk such as yoga have been shown to improve volitional measures of inspiratory and expiratory muscle strength (REF). These exercises result in

an increase in IAP and P_{di} (REFS). The increase in P_{di} serves three important functions: i) to facilitate the evolution of IAP, ii) to prevent spinal injury from axially directed compressive forces on the spine and facilitate postural control and iii) to prevent the transmission of the large intra-abdominal pressure to the thoracic cavity. The transdiaphragmatic pressure generated during resistance training is often in excess of 65% $P_{di,max}$ and can result in respiratory muscle fatigue (Gomez, Al bilbeisi and McCool, Suzuki 1999). The relative force output of the diaphragm is also far greater than that required during a typical inspiratory muscle training regimen which results in similar increases in $P_{I,max}$, $P_{E,max}$ and T_{di} (Brown, Downey). Interestingly improvements in respiratory muscle strength have also been observed following 4 wk whole-body interval and endurance training (Dunham and Harms). These data suggest that the respiratory muscles are incredibly sensitive to the intra-thoracic pressure swings experienced during resistance and endurance training regimens. In agreement with this, we attribute the greater respiratory muscle strength in POWER to the repeated exposure of these muscles to severely high IAP when performing lifting tasks as illustrated by the significant positive correlation between diaphragm thickness and the total weight lifted in the three manoeuvres (Figure 3). Our data therefore support previous studies illustrating greater respiratory muscle function in resistance trained individuals and we are the first to characterise this in world class Powerlifters.

Pulmonary function

We have demonstrated that pulmonary function was similar between groups which disagrees with our hypothesis. To the authors knowledge no data exist regarding the effects of resistance training upon pulmonary function in healthy individuals. Interestingly, whole body interval and endurance training (REF) and moderate intensity pressure threshold inspiratory muscle strength training also fails to affect pulmonary function in healthy individuals (Brown). However, high intensity flow resistive respiratory muscle training has been shown to increase vital capacity and total lung capacity (Enright). In this study, increased lung volumes were not attributed to adaptation of the

lung parenchyma but rather an increased ability to inflate the lungs. These findings are unsurprising given that lung tissue only demonstrates plasticity during hypoxia immediately following birth or with up to 50% surgical denervation (Wagner 2005). Despite the greater inspiratory and expiratory muscle strength in POWER, we observed no difference in peak inspiratory or expiratory flow rates, respectively relative to CON (Table 2). As with all skeletal muscles, the respiratory muscles demonstrate a force-velocity (pressure-flow) relationship and adhere to the specificity principle in response to training (REF). The isometric nature of inspiratory and expiratory muscle contraction during powerlifting tasks was therefore unlikely to have resulted in improvements in the maximal shortening velocity of these muscles. Our results are consistent with previous research whereby high inspiratory pressure threshold loading with low velocity of shortening inspiratory muscle training improved inspiratory muscle strength *per se* with no change in inspiratory flow rates (ROMER MC 2003). It would therefore be interesting to investigate the pressure-flow-power relationship throughout a programme of resistance training in untrained individuals to understand this further. Our study illustrates for the first time that in elite powerlifters whole body resistance training improves respiratory muscle strength *per-se* with no effect upon pulmonary function.

Practical implications

Respiratory muscle weakness is a common feature of ageing and some clinical conditions such as neuromuscular disease or unexplained breathlessness (Polkey et al 2007) which may exacerbate respiratory muscle fatigue and / or the development of respiratory failure. The structural and functional changes in the respiratory musculature due to inspiratory muscle weakness increase the work of breathing (Johnson et al 2007) and therefore the perception of breathing effort for a given exercise intensity (Jolley and Moxham 2009 ERR). It is appropriate to suggest that individuals who perform regular resistance training will improve respiratory strength (DePalo) which has been shown to improve exercise tolerance (Huang et al. 2011) and quality of life (Aznar-Lain et al. (2007). Accordingly, Powerlifters and other individuals engaged in weight lifting may have a

greater protection from respiratory muscle dysfunction and the negative effects of ageing and chronic disease states than sedentary individuals. Therefore the role of resistance training upon respiratory health across the lifespan and in the pulmonary rehabilitation program in clinical, recreational and trained individuals provides an intriguing avenue for future research.

In conclusion, this study demonstrates that world class Powerlifters have significantly greater inspiratory and expiratory muscle strength and diaphragm thickness yet similar pulmonary function compared to a group of matched untrained controls. Improvements in respiratory muscle strength and thickness following acute and chronic resistance training may serve to improve resistance from respiratory muscle weakness encountered with ageing and in some chronic disease states.

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Table 1 Physical characteristics of the powerlifting (POWER) and control (CON) groups.

	POWER (n=10)	CON (n=10)
Age (years)	28.0 ± 11.3	25.0 ± 4.1
Height (m)	1.75 ± 0.5	1.77 ± 0.6
Body mass (kg)	100.7 ± 24.8	97.3 ± 20.9
Body fat (%)	24 ± 10	22 ± 8
Training history (years)	10 ± 12	-
Training frequency (days·wk ⁻¹)	3.8 ± 0.4	-
Squat (kg)	269 ± 101 (140 - 467.5)	-
Bench Press (kg)	192.5 ± 73.4 (90 - 320)	-
Deadlift (kg)	264 ± 44 (195 - 325)	-
Total lifted (kg)	735 ± 211 (425 - 1062.5)	-

Values are expressed as means ± SD. Values in parentheses represent the data range.

Table 2 Inspiratory and expiratory muscle strength, pulmonary function and diaphragm thickness for the powerlifting (POWER) and the control (CON) group.

	POWER (n=10)	CON (n=10)
$P_{I,max}$ (cmH ₂ O)	156.8 ± 24.9 (140.6 ± 29.6 ^b)	122.7 ± 35.5 ^a (105.8 ± 30.61)
$P_{E,max}$ (cmH ₂ O)	199.9 ± 66.4 (132.2 ± 50.7 ^b)	153.4 ± 41.6 (97.7 ± 27.14)
FVC (L)	4.9 ± 0.9 (95.8 ± 12.9)	5.1 ± 0.8 (96.6 ± 12.8)
FEV ₁ (L)	4.0 ± 0.5 (94.6 ± 9.6)	4.4 ± 0.5 (99.7 ± 9.6)
FEV ₁ /FVC (%)	83.5 ± 5.5 (101.7 ± 7.2)	87.6 ± 3.9 (105.9 ± 4.6)
PEF (L·s ⁻¹)	10.2 ± 1.5 (83.3 ± 13.6)	10.7 ± 0.9 (85.3 ± 6.1)
PIF (L·s ⁻¹)	7.5 ± 1.2	8.4 ± 1.6

^a $P < 0.05$ vs. POWER, ^b $P < 0.05$ greater than predicted. Values are expressed as means ± SD. Data in parentheses represent the percent of predicted values (Quanjer et al. 1993; Wilson et al. 1984). $P_{I,max}$ = maximal inspiratory mouth pressure; $P_{E,max}$ = maximal expiratory mouth pressure; FVC = forced vital capacity; FEV₁ = forced expiratory volume in 1 s; PIF = peak inspiratory flow; PEF = peak expiratory flow rate.

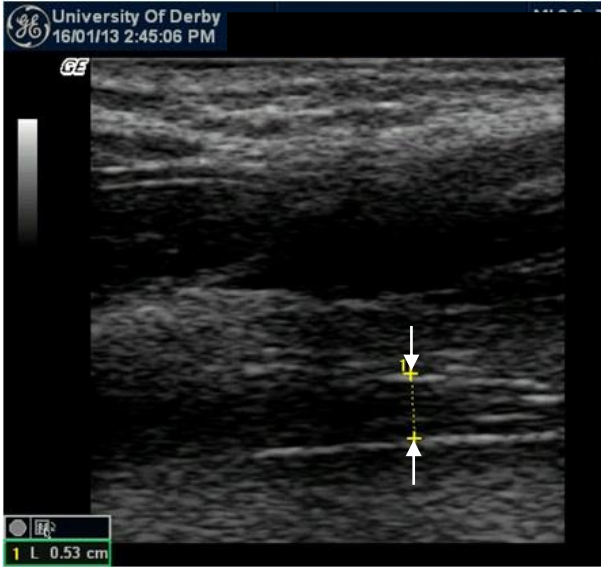
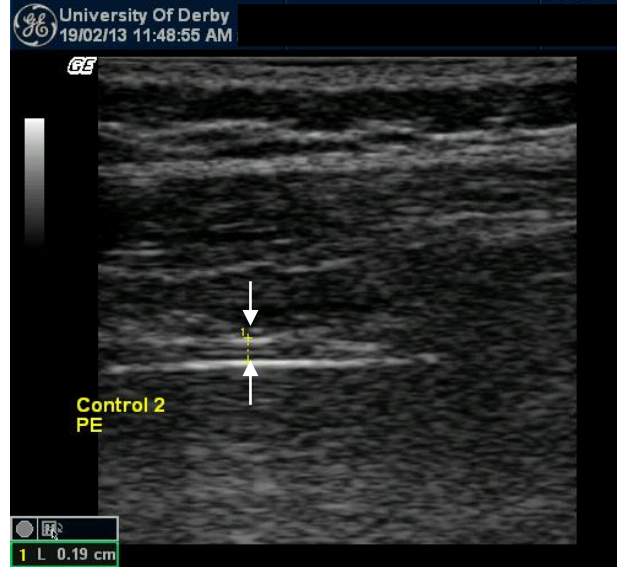
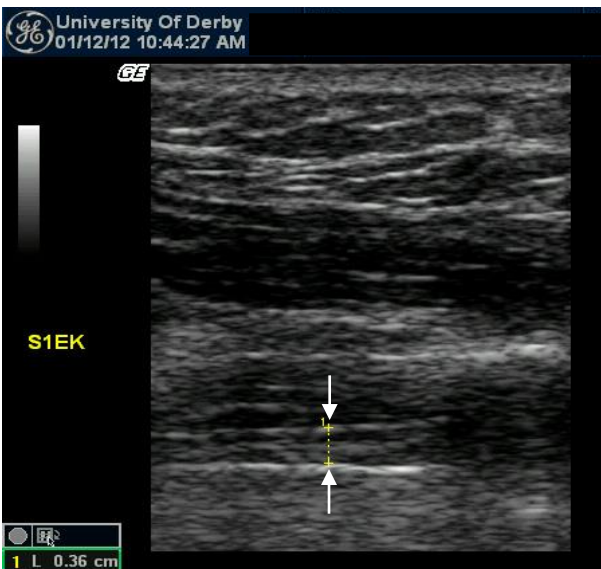
A: POWER**B: CON****C: POWER****D: CON**

Figure 1 Diaphragm thickness (T_{di}) ultrasound image for (A) heavy (120kg) World class powerlifter (POWER) and (B) matched control (CON) and (C) light (74kg) World class powerlifter and (D) matched control. The diaphragm was identified as a hypo-echoic layer between the highly reflective pleural (top arrows) and peritoneal (bottom arrows) membranes.

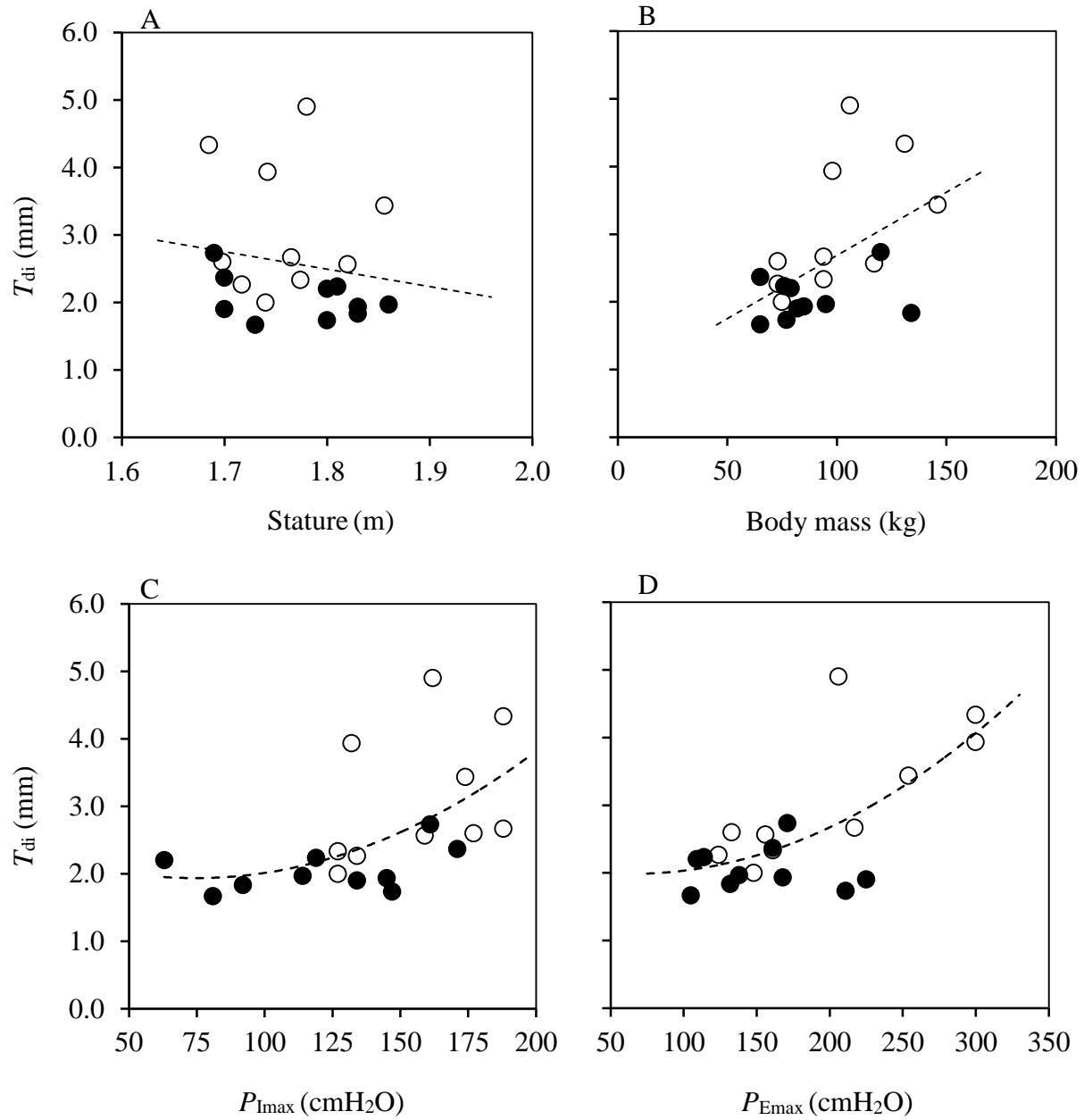


Figure 2 Relationship between diaphragm thickness (T_{di}) and A) stature, B) body mass, C) maximal inspiratory pressure ($P_{I\max}$) and D) maximal expiratory pressure ($P_{E\max}$) in World class powerlifters (○) and matched untrained control group (●).

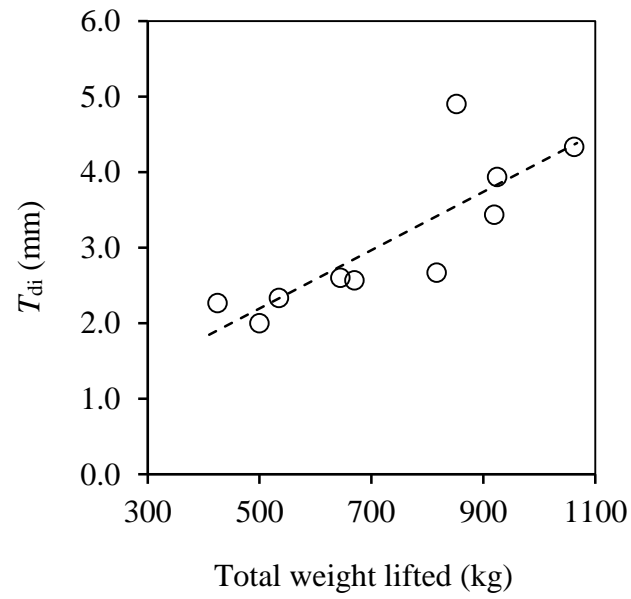


Figure 3 Relationship between diaphragm thickness (T_{di}) and total weight lifted (sum: squat, bench press, deadlift) in World class powerlifters.